A management strategy evaluation of Pacific Hake: methods, conditioning and scenarios

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Abstract

A key question regarding management of exploited species is how spatial structure influences the estimation and derivation of management quantities. Pacific hake is the largest ground fish fishery on the Pacific West Coast, with over 300,000 tons annual catch in recent years. The Pacific hake stock spans Canadian and U.S. exclusive economic zones, and management is directed through a binational treaty, where quotas are based on a harvest control rule and a fixed allocation to each country. There are two pertinent hypotheses regarding how spatial structure of the stock can affect management: 1) demographic distribution shifts - Pacific hake spawn in the southern California Current (U.S. territory)

and the extent of northward migration (towards and into Canadian territory) is related to individual size, and 2) climate-driven distribution shifts – prevailing ocean conditions, including climate change, cause distributional shifts of the stock. We use management strategy evaluation (MSE) to evaluate how alternative hypotheses about spatial stock structure influence robust management choices. The MSE employs closed-loop simulations with an operating model that represents real life complexity of hake biology and an estimation model similar to the stock assessment model used for Pacific hake. By explicitly modeling spatial structure (i.e., movement and spatial recruitment) in the operating model, we can evaluate the performance of control rules and reference points that do not account for spatial differences. The results of the MSE are contextualized in regards to improving current management and assessment of the binational stock.

Introduction

The US-Canada Agreement for Pacific Hake was fully implemented in 2012 when the stock assessment was first conducted by the newly appointed Joint Technical Committee (JTC) and first reviewed by the newly formed Scientific Review Group (SRG). Both the JTC and SRG reports that year highly recommended embarking on a Management Strategy Evaluation (MSE) as a tool to explore a variety of issues associated with management of the hake fishery, including data collection (frequency of acoustic surveys), assessment methods (treatment of selectivity), and management (performance of the harvest control rule) (SRG, 2012; Stewart, Forrest, Taylor, Grandin, & Hicks, 2012).The Pacific Hake fishery had also been certified as sustainable by the Marine Stewardship Council in 2010 with the evaluation of the harvest control rule in an MSE framework included as a condition for maintaining the certification (Devitt, Stocker, Collie, & Pedersen, 2009).

An initial iteration of the MSE was conducted during the period 2012 to 2015, with results presented as appendices to the 2013, 2014, and 2015 stock assessments (Hicks, Taylor, Grandin, Taylor, & Cox, 2013; I. G. Taylor, Grandin, Hicks, Taylor, & Cox, 2015; N. Taylor, Hicks, Taylor, Grandin, & Cox, 2014). The SRG reviews of these results were largely supportive of the MSE work, but noted the need for more complexity in the operating model (OM) to provide a more robust test of the performance of the assessment model specifically and the management system more generally. Recommendations from SRG reports during this iteration included the following:

- “The SRG encourages the JTC to consider including structural mismatches in future MSE experiments to evaluate the model uncertainties that are inherent but currently unmeasured in the stock assessment results.” (SRG, 2014).
- “The SRG concludes that developing a spatially explicit MSE operating model is necessary to examine issues involving fishing by the US and Canada with spatial dimensions, such as the availability of fish in each country.” (SRG, 2015).
- “The SRG concludes that developing an operating model that is structured differently from the assessment model will be a critical element of conducting further MSE work for Pacific Hake. A spatially explicit operating model is likely necessary to examine issues involving fishing by the US and Canada with spatial dimensions, such as the availability of fish in each country. Other areas of fruitful inquiry with an MSE include evaluating alternative approaches to modeling selectivity of the fishery, evaluating juvenile indices, and management approaches and procedures for stocks with episodic strong recruitment events.” (SRG, 2016).

Development of this more complex operating model was stalled due to lack of staff time available to do the work. The addition of an MSE coordinator position at NOAA’s Northwest Fisheries Science Center in 2017 (filled by K. Marshall) and a postdoctoral research position in 2018 (filled by N. Jacobsen) allowed this next iteration of MSE work to begin and a proposed work plan was presented at the 2018 SRG meeting. The 2018 SRG report (SRG, 2018) supported implementation of the work plans and repeated the recommendation that "the OM must be structurally different from, and more complex than, the assessment model".

This document describes a new spatially explicit operating model and other aspects of the MSE which have been developed over the past year, incorporating feedback gathered at the Joint Management Committee (JMC) meetings in March and July of 2018 and three phone meetings of a newly formed MSE Working Group that occurred between the two JMC meetings. The 2018-19 U.S. federal government shutdown delayed progress on the MSE, so the results presented here should be considered preliminary and are included to allow the SRG to have a preview of results that will be forthcoming in 2019 and an opportunity to provide feedback on how the results are communicated.

Goals of the MSE

In March 2018, together the JMC and analysts articulated goals for this iteration of the Pacific Hake MSE. They were, in no particular order:

- Evaluate the performance of current hake management procedures under alternative hypotheses about current and future environmental conditions
- Better understand the effects of hake distribution and movement on both countries' ability to catch fish
- Better understand how fishing in each country affects the availability of fish to the other country in future years

Methods

The management strategy evaluation closed-loop simulation model consists of four individual components (Figure 1): 1) an operating model (OM), 2) an observation model, 3) an estimation model (EM), and 4) a management model. Each component is described in detail below.

Operating model.

The operating model is a standard age-based model with movement occurring between two spatial areas. The time scale of the model is four seasons per year, which allows fish to move within a year, and subsequently return to spawn at a given area in the beginning of the following year. We denote years as y and the general time scale as t to distinguish between processes that happen among years and within seasons. We define the equations for the operating model below.

Equilibrium abundance

To initialize the model, we calculate the unfished distribution based on natural mortality and unfished recruitment.

$$N_a = \begin{cases} R_0 e^{-\sum_a M_a} & if\ a < A \\ \frac{N_{A-1} e^{\sum_a M_a}}{1-e^{-M_a}} & if\ a = A \end{cases} \quad (1)$$

Where R_0 is the unfished recruitment, a is age, A is the plus-group age, and M_a is the natural mortality at age. The unfished age distribution results in unfished spawning biomass as

$$S_0 = 0.5 \sum_a \psi_a N_a (2)$$

where ψ_a is the age specific fecundity and 0.5 assumes that half of the population is female.

Initial conditions

The initial conditions leading up to the fishery also includes A number of years with recruitment deviations. The first year of the simulation is therefore initialized with the following age distribution

$$N_a = \begin{cases} R_0 e^{-\sum_a M_a} e^{-0.5\sigma_R^2 b_y + \tilde{R}_y} & if\ a < A \\ \frac{N_{A-1} e^{\sum_a M_a}}{1-e^{-M_a}} e^{-0.5\sigma_R^2 b_y + \tilde{R}_y} & if\ a = A \end{cases} (3)$$

Where N_a is the numbers at age. σ_R is the standard deviation of recruitment deviations, b_y is a bias adjustment factor (Methot, Taylor, & Chen, 2011). We assume $b_y = 0$ in the years leading up to the fishery. $\tilde{R}_y$is annual recruitment deviations that are assumed to be normally distributed with 0 mean.

Growth

Growth follows the empirical weight at age used in the Pacific hake stock assessment (Grandin et al., 2016). In years where the empirical weight at age is unavailable, we use the average weight at age. The weight at age is different depending on the source, i.e., there is a weight available for the fishery, the survey, the spawning biomass, and in the middle of the year.

Reproduction

Recruitment is assumed to occur in the beginning of the year and follows a Beverton-Holt stock recruitment curve with annual deviations

$$R_y = \frac{4hR_0S_y}{S_0(1-h)+S_y(5h-1)} e^{-0.5\sigma_R^2 b_y + \tilde{R}_y} (4)$$

h is steepness of the stock recruitment curve and S_y is the spawning biomass in that year calculated as $S_y = \sum_a N_{a,y} w_a E_a$ where E_a is the age specific fecundity.

We use bias correction, b, as an input to the model following (Methot et al., 2011)

$$b_y \begin{cases} 0 & y \le y_1^b \\ b_{max}\left(1 - \frac{y-y_1^b}{y_2^b - y_1^b}\right) & y_1^b < y < y_2^b \\ b_{max} & y_2^b < y < y_3^b \\ b_{max}\left(1 - \frac{y_3^b - y}{y_4^b - y_1^b}\right) & y_3^b < y < y_4^b \\ 0.5 & y_4^b \le y \end{cases} (5)$$

where $y_1^b \dots y_4^b$ are breakpoints for the change in bias adjustment. Bias adjustment in future projections is implemented in the operating model such that under no fishing $S \approx S_0$. Since recruitment is lognormally distributed, not implementing a bias adjustment in the future would cause the average biomass to be higher than the unfished biomass. In future years we therefore set $b = 0.5$, which leads to a median $\frac{SSB}{SSB0} \approx 1$ (Figure 2)

Among years the model is projected forward in time using the standard equations

$$N_{y+1,a+1} \begin{cases} R_y & if\ a = 0 \\ N_{t,a}e^{-Z_{t,a}} & if\ 1 \leq a \leq A-1 \\ N_{t,A}e^{-Z_{t,a}} + N_{t,A}e^{-Z_{t,a}} & if\ a = A \end{cases} \quad (6)$$

Within a year the fish are subject to the total mortality, $Z_{t,a} = s_{a,y}F_t + M$ where s_a is the age and year specific fishing selectivity, and F_t is the fishing mortality occurring in that particular season (in the case of going in between years from season 4 to season 1), and *M* is natural mortality assumed constant across ages and time periods. The number of fish surviving to the next season is then calculated as

$$N_{t+1,a} = N_{t,a}e^{-Z_{t,a}} (7)$$

Fishing

We model selectivity for both the fishery and the scientific survey as an approximation of a trawl selectivity curve with four and five parameters for the survey and fishery, respectively. We assume that selectivity does not change within a year, and that the acoustic survey selectivity is constant. The fisheries selectivity is constant from the years 1965 to 1991, and from 2018 and onwards. From 1991-2017 fisheries selectivity is furthermore calculated every year as deviations from the constant selectivity. These assumptions are based on those made in the 2018 stock assessment model (Edwards et al., 2018). The years where selectivity is constant it is modeled as

$$s_a = \exp\left(s'_a - s'_{\max}\right) (8)$$

Where s'_a is the cumulative sum over ages of the selectivity parameter p

$$s'_a = \sum_{a=a_{min}}^{a_{max}} p_a \ (9)$$

Finally, s'_{max} is the maximum value of s'_a. When $a < a_{min}$ | $s_a = 0$, and when $a > a_{max}$ | $s_a = s_{a_{max}}$.

In the years selectivity is variable p_i is allowed to vary as

$$p_{a,y} = p_a + \epsilon_{a,y} \ (10)$$

where $\epsilon_{a,y}$ is an annual selectivity deviation assumed normally distributed with variance σ_{sel}.
a_{min} denotes the age below which $s_a = 0$ and a_{max} denotes the age above which $s_a = s_{a-1}$.

Movement

To model the spatial distribution of Pacific hake we assume there are n areas, between which the fish can move (i.e., 2 areas). First we define the first year of the simulation

$$N_{0,a,i} = N_{0,a}\omega_{0,i} (11)$$

Where ω_0 is an n_{space} length vector that sums to 1 that defines the fraction of fish in each of the spatial areas and i denotes the areas from $i \ldots n_{space}$ going from North to South. When the model is projected forward in time, fish move between areas depending on their age, the season, and which area they are in at the beginning of that season. Specifically, we model the movement as a matrix that determines the number of fish that leave an area. We assume that movement and mortality occur at the same time, but for simplicity we do not denote the mortality in the equations below

$$N_{t,a,i} \begin{cases} N_{t-1,a}\omega_{t,a,2} - N_{t-1,a}\omega_{t,a,1} & if\ i = 1 \\ N_{t-1,a}\omega_{t,a,i-1} + N_{t-1,a}\omega_{t,a,i+1} - N_{t-1,a}\omega_{t,a,i} & if\ 1 < i < n \\ N_{t-1,a}\omega_{t,a,n-1} - N_{t-1,a}\omega_{t,a,n} & if\ i = n \end{cases} \text{(12)}$$

where $\omega_{t,a,i}$ is the movement matrix.

Movement is modeled as a saturating function of age defined as

$$\omega_{a,i} = \frac{\kappa_i}{1 + \mathrm{e}^{(-\gamma(a - a_{50}))}}$$

Where κ is the maximum movement rate, α determines the slope towards the maximum, and a_{50} is the age at 50% of maximum movement rate. There are two other main assumptions to movement:

1) For the northern area, movement in the last season of the year is assumed to be constant across all ages: $\omega_{a,i} = \kappa_{return}$. This values is set to 80% in all but the climate scenario. This causes most of the spawning biomass present in the Northern part move south to spawn in the last season of the year, so they are effectively present to spawn first of January in the following year
2) When the fish have moved North during the year, they only rarely (5%) move South again before the last season, where the spawning biomass migrates.

The movement in each season is visualized inFigure 3.

Catch

We model the catch with the standard Baranov catch equation, but applied to each season, and area

$$C_{t,a,i} = \frac{s_{y,a}F_t}{Z_{t,a,i}}(1 - e^{-Z})N_{t,a,i}w_{t,a} \text{(13)}$$

where $w_{t,a}$ is the empirical weight at age. The operating model calculates the fishing mortality, F_t, each season based on the catch using Popes approximation (Methot & Wetzel, 2013; Pope, 1972).

Observation model data generation

The operating model produces output similar to the empirical data observed in the fishery and acoustic survey. From the fishery, the model outputs total catch every year

$$C_y = \sum_t \sum_a \sum_i C_{t,a,i} \text{ (14)}$$

Both the fishery and the survey report age compositions per year φ_s, φ_F . For the fishery the numbers at age in the catch is found by dividing by the individual weight.

$$\varphi_{a,y} = \frac{N_{y,a,c}}{\sum_{a=1}^{A} N_{y,a,c}} \text{(15)}$$

$N_{y,a,c}$ is the abundance of individuals at age in the catch. All ages over 15 are summed up for both the fishery and the scientific survey.

The survey is reported as the total biomass targeted by the survey, and thus does not report area specific biomass. The survey is biannual by default, but we explore alternative scenarios of survey frequency below.

$$B_y = q s_a N_{y,a} w_{y,a} \epsilon_s \text{(16)}$$

Where q is the catchability coefficient, and s_a is the survey selectivity. We assume that the survey takes part in the second quarter of the year. Measurement error in the survey is distributed as $\epsilon_s \sim Lognormal\left(C, \sigma^2_{survey}\right)$. The standard deviation is comprised of two different values $\sigma^2_{surv} + \sigma^2_{s,y}$ where σ^2_{surv} is a constant variance, and $\sigma^2_{s,y}$ is a standard deviation specific to the survey years.

Estimation model

The estimation model (EM) is a standard age-based model with the same dynamics as the operating model (i.e., the same equations as above, but excluding equation 11-12). Furthermore, the timestep is annual rather than having 4 seasons per year. We estimate 274 parameters in the model (from year 1965-2017) with the number of parameters increasing with two per extra year modeled into the future. The parameters are estimated by minimizing the negative joint log-likelihood function comprised of 8 different components, of which 4 are fit to data and 4 are penalty functions for parameter deviations. In the notation below, a ~ denotes 'data'.

Data fitting

- Fit of the survey data as a log-normal distribution $\tilde{B}_y \sim Lognormal(B_y, \sigma^2_{s,adj})$The adjusted standard deviation is $\sigma^2_{s,adj} = \sigma^2_s + \sigma^2_{s,y}$ where σ^2_s is a constant survey variance term accounting for survey error, and $\sigma_{s,y}$ is an additional time varying variance term calculated externally as a part of the survey krieging and extrapolation only in survey years
- Fit to the natural logarithm of total catches as a lognormal distribution $\tilde{C}_y \sim Lognormal(C, \sigma^2_C)$ with standard deviation $\sigma^2_C = 0.01$ to closely match observed and modeled catches.
- A Dirichlet-Multinomial fit to age composition data from both survey and catches $-logL(\varphi, \theta | \widetilde{\varphi}, n) = log\Gamma(n + 1) - \sum((log\Gamma(n\tilde{\varphi} + 1) + log\Gamma(\theta n) - \log\Gamma(n + \theta n) +$ $\sum(\log\Gamma(n\widetilde{\varphi} + \theta n \varphi) + log\Gamma(\theta n \varphi)$ where *n* is the number of samples in the observations, and θ is the Dirichlet-Multinomial shape parameter

Penalty functions

- Penalty for recruitment deviations away from 0 as $L_R = 0.5\left(\frac{\widetilde{R^2_y}}{\sigma^2_R} + b_y \log(\sigma^2_r)\right)$
- Penalty for selectivity deviations away from 0 as $L_{sel} = 0.5\left(\frac{\epsilon^2_{a,y}}{\sigma^2_{sel}}\right)$
- A penalty on deviations on steepness, *h*, as a beta-function $-\log\,(L_h) \sim beta(h, \alpha, \beta)$ where $\beta = \tau\mu$ and $\alpha = \tau(1 - \mu)$. $\mu = \frac{(h_{prior} - h_{mini})}{h_{maxi} - h_{mini}}$ and $\tau = \frac{\left((h_{prior} - h_{min})(h_{max} - h_{prior})\right)}{\sigma^2_h} - 1$
- A penalty for natural mortality log-normal deviations away from 0.2 $L_M = 0.5\left(\frac{(\log(M) - \log\,(0.2))}{0.1}\right)^2$

The estimation model is fitted in the software 'TMB'. To fit a model in TMB, a template is constructed where the likelihood function is specified as a function of the biological model. The template is then called from R which uses a gradient based non-linear minimizer to identify the value of the parameters that minimize the likelihood function.

Management model

We use a stepwise F_{40} management model that determines the total allowable catch based on the spawning potential ratio (SPR). The spawning potential ratio (SPR) is calculated as

$$N_{a,SPR} = \begin{cases} 1e^{-\sum_a Z_a} & if\ a < A \\ \frac{N_{A-1}e^{\sum_a Z_a}}{1-e^{-Z_a}} & if\ a = A \end{cases} \quad (17)$$

$$SPR = \frac{0.5 \sum_a N_{SPR} w_a E_a}{S_0} \quad (18)$$

Where the goal is to reach SPR = 0.4 by adjusting the F component of Z. We then convert the fishing mortality rate that leads to SPR = 0.4, F_{eq} , to a harvest rate as $H = 1 - \exp(-F_{eq})$, and set the total allowable catch (TAC) according to

$$TAC_{y+1} = \begin{cases} 0 & S_y/S_0 < 0.1 \\ HV_y\left(\left(S_y - 0.1S_0\right)\left(\frac{\frac{0.4S_0}{S_y}}{0.4S_0 - 0.1S_0}\right)\right) & 0.4 \geq \frac{S_y}{S_0} \geq 0.1 \\ HV_y & \frac{S_y}{S_0} > 0.4 \end{cases} \quad (18)$$

Here $V_y$is the biomass available to catch for the fishery (i.e., $\sum N_{a,y} s_a w_a$).

Conditioning of operating model

The operating model is based on the equations described above. An important step of the MSE is to condition the operating model, where the model is evaluated against available data. The data available for the conditioning are

- Catches
- Age composition in catches from Canada and the US (by fleet)
- Spatially explicit survey biomass estimate
- Spatially explicit survey age compositions

To initialize the model, we used a range of the estimated parameters from the maximum likelihood assessment model (Table 1). Parameters from the assessment model should be used with care, as they depend on the assumptions and constraints imposed by that model. Nevertheless, by using them as a starting point for the model condition, the operating model will produce retrospective patterns of survey estimates and catches that are comparable in scale to the observed quantities. Parameters that are unique to the operating model here are parameters regarding movement and country specific selectivity. Comparison between the data used in the conditioning and the operating model output is shown in Figure 4, Figure 5, and Figure 6.

Scenarios

A goal of this MSE exercise is to investigate the performance of the current harvest strategy, given current and future uncertainty. To evaluate the performance of the harvest strategy, we investigate a range of performance metrics to evaluate how they meet a set of pre-specified objectives (Table 2). The objectives and metrics for use in the MSE have been chosen in collaboration with the Pacific Hake MSE working group, which consists of stakeholders, JMC and JTC members, and researchers from the

Northwest Fisheries Science Center. The current objectives primarily aim at a sustainable coastwide fishery, and thus require summation of catches and abundances in the specified areas.

We ran five sets of MSE simulations for this meeting, all representing changes to the operating model. The scenarios are described in detail below:

- Catch scenarios

The catch scenarios investigate the consequences of setting TAC in four different ways. They are: 1) set the TAC using the harvest control rule specified in the Treaty, 2) set the TAC using a rule that mimics how the quota has been set by the JMC in the past, 3) set that TAC using a rule that mimics what the realized catch has been in the past, and 4) set the TAC to 50% of the Treaty HCR, but apply a floor (minimum TAC) of 180000 tons (Figure 7).

- Movement scenarios

The movement scenarios assume different relationships between movement rate and fish age in the operating model. We test three different movement rates, low movement ($\kappa = 0.15, a_{50} = 5$), medium movement rate ($\kappa = 0.4, a_{50} = 8$), and a high movement rate ($\kappa = 0.6, a_{50} = 4$)

- Climate scenarios

The climate scenarios are hypothetical scenarios that tests the consequences of assuming that changing ocean conditions (e.g., increases in temperature) will cause increasing movement rates, and reduced rates of fish returning south to spawn (Figure 8). We model two climate scenarios, a slow increase in max movement rate ($\Delta\kappa = 0.01\ yr^{-1}$, and $\Delta\kappa_{return} = 0.005 yr^{-1}$), where Δ represents the change in movement rate (we set $\max(\kappa) = 0.8$)). The second scenario represents a higher increase in movement in the future ($\Delta\kappa = 0.04\ yr^{-1}$, and $\Delta\kappa_{return} = 0.02 yr^{-1}$). We compare the two to a baseline scenario of no increase in movement.

- Selectivity scenarios

We investigate selectivity scenarios, where the two countries have different fishery selectivities. We test three scenarios (Figure 9), 1) the baseline conditioned model, where Canada catches larger fish than the US, 2) a scenario where the US starts to target fish heavily at age 2, where Canada still targets larger fish, and 3) both countries have the same selectivity equal to the 2018 estimated selectivity in the assessment.

- Survey frequency scenario

The survey frequency scenario investigates the potential consequences of performing acoustic surveys either every second year (current situation), every third year, or alternatively every year. The survey records both the age compositions and an index of abundance.

Figures and tables

Table 1: Parameters used in the operating and estimation model. Value denotes the value in the operating model. If the parameter is not estimated it is the same in the estimation model. n denotes the number of parameters estimated.

Parameter	Value	Estimated	Explanation
q	1	No	Catchability coefficient
σ_R^2	1.4	No	SD of recruitment deviations
θ_C		Yes	Dirichlet-Multinominal parameter in Catch
θ_{survey}		Yes	Dirichlet-Multinominal parameter in survey
h	0.8	Yes	Steepness
h_{min}	0.2	No	Shape parameter for steepness prior distribution
h_{max}	0.1	No	Shape parameter for steepness prior distribution
h_{prior}	0.777	No	Shape parameter for steepness prior distribution
σ_h^2	0.117	No	Standard deviation for steepness prior distribution
R_0	2108316	Yes	Unfished recruitment
M	0.214	Yes	Natural mortality
σ_s^2	0.26	Yes	Survey standard deviation
$p_{a,C}$ (n = 5)	[12,2.5,1.5,1.2,1.6]	Yes	Fisheries selectivity
$p_{a,survey}$ (n = 4)	[1.77,0.80,1.36,1.45]	Yes	survey selectivity
$\tilde{R}$ (n = 72)	$N(0,\sigma_R^2)$	Yes	Recruitment deviations
$\epsilon_{a,y}$ (n = 135)	$N(0,\sigma_{sel}^2)$	Yes	Selectivity deviations
σ_{sel}^2	1.4	No	Standard deviation of selectivity
F_y (n = 52)		Yes	Fully selected fishing mortality
n_{space}	2	No	Number of spatial cells in the OM
κ	[0.1;0.75]	No	Maximum movement rate
κ_{return}	0.8	No	Fraction of returning spawners
γ	0.5	No	Slope of movement rate
a_{50}	[5;10]	No	Age at 50% maximum movement rate

Table 2: Goals, objectives and performance metrics for the Pacific hake management strategy evaluation.

ID	Goal	Objective	State	P	Time Period	Performance metric
Manage the Pacific Whiting resources in a precautionary and sustainable manner						
1	Minimize risk of severe overfishing and closing the fishery	Spawning biomass is above 10 percent of unfished biomass in 95 percent of the years over a 30-year period.	$B > B_{10\%}$	0.95	Long-term (t=1,…30)	$P(B > B_{10\%}) = \frac{\sum_{t_1}^{t_2} \mathrm{I}(B_t > B_{10\%})}{t_2 - t_1 + 1}$
2	Maintain biomass above **a threshold that triggers a reduction in harvest rate a high percentage of the time**	Spawning biomass is above 40 percent of unfished biomass in 75 percent of the years over a 30-year period.	$B > B_{40\%}$	0.75	Long-term (t=1,…30)	$P(B > B_{40\%}) = \frac{\sum_{t_1}^{t_2} \mathrm{I}(B_t > B_{40\%})}{t_2 - t_1 + 1}$
3	If the stock drops below a **threshold that triggers a reduction in harvest rate**, return biomass to above the threshold within 3 years with high probability	If spawning biomass drops below 40 percent of unfished biomass, the probability that it exceeds the threshold within 3 years is greater than 90 percent.	*If $B < B_{40\%}$*, return to $B > B_{40\%}$ within 3 years	0.90	Long-term (t=1,…30)	*Formula definition in progress*
Alt 3.	*Avoid closing the fishery.*	*Fishery is open in both Canada and the US in 95% of the years over 30 years.*	*$F_{CA}>0$ and $F_{US}>0$ F_{CA} = fishing mortality rate in Canada F_{US} = fishing mortality rate in US*	*0.95*	*Long-term (t=1,…30)*	$P(F_{CA} > 0 \,\&\, F_{US} > 0) = \frac{\sum_{t_1}^{t_2} \mathrm{I}(F_t^{CA} > 0 \,\&\, F_t^{US} > 0)}{t_2 - t_1 + 1}$
Both parties can achieve their intended benefits under the treaty						
4a	Each country has the opportunity to attain their allocation of the TAC as specified in the treaty.	The exploitable (age 2+) biomass in Canadian waters during the fishing season is greater than the Canadian allocated TAC > 90 percent of years	$V_{CA} > 0.2612TAC/u_{CA}$* V_{CA}=age 2+ biomass in Canada u_{CA}*= intended Canadian harvest rate	0.90	*Long-term (t=1,…30)*	$P(V_{CA} > 0.2612TAC/u_{CA}) = \frac{\sum_{t_1}^{t_2} \mathrm{I}(V_{CA} > 0.2612TAC_t/u_{CA})}{t_2 - t_1 + 1}$

ID	Goal	Objective	State	P	Time Period	Performance metric
4b		The exploitable (age 2+) biomass in US waters during the fishing season is greater than the US allocated TAC > 90 percent of years	V_{US} > 0.7388TAC/u_{US}* V_{US}=*age 2+ biomass in US* u_{US}*= intended US harvest rate	0.90	*Long-term (t=1,…30)*	$P(V_{US} > 0.7388TAC/u_{US}) = \frac{\sum_{t_1}^{t_2} \mathrm{I}(V_{US} > 0.7388TAC_t/u_{US})}{t_2 - t_1 + 1}$
Alt. 4	*Achieve a spawning biomass target so that both parties can obtain benefits.*	*The spawning biomass is greater than a target biomass with probability 0.5.*	*B > 1.2$B_{40\%}$*	*0.5*	*Long-term (t=1,…30)*	$P(B > 1.2 * B_{40\%}) = \frac{\sum_{t_1}^{t_2} \mathrm{I}(B_t > 1.2 * B_{40\%})}{t_2 - t_1 + 1}$
Yield Objectives						
5	Maintain low catch variability (AAV).	*Given 1-3(or 4) are satisfied*: Year to year changes in catch should average less than 15%	AAV < 15%		Long-term t=1,…,*30*	$AAV = \frac{\sum_{t_1}^{t_2} \lvert C_t - C_{t-1} \rvert}{\sum_{t_1}^{t_2} C_t}$
6a	Maximize catch in the short-term	*Given 1-5 are satisfied*, achieve maximum coastwide catch in the short-term	max($\bar{C}$)		Short-term (t=1,*…10)*	$\bar{C} = \frac{1}{t_2 - t_1 + 1} \sum_{t_1}^{t_2} C_t$
6b	Maximize catch in the long-term	*Given 1-5 are satisfied*, achieve maximum coastwide catch in the long-term	max($\bar{C}$)		Long-term (t=21,..30)	$\bar{C} = \frac{1}{t_2 - t_1 + 1} \sum_{t_1}^{t_2} C_t$

Figures

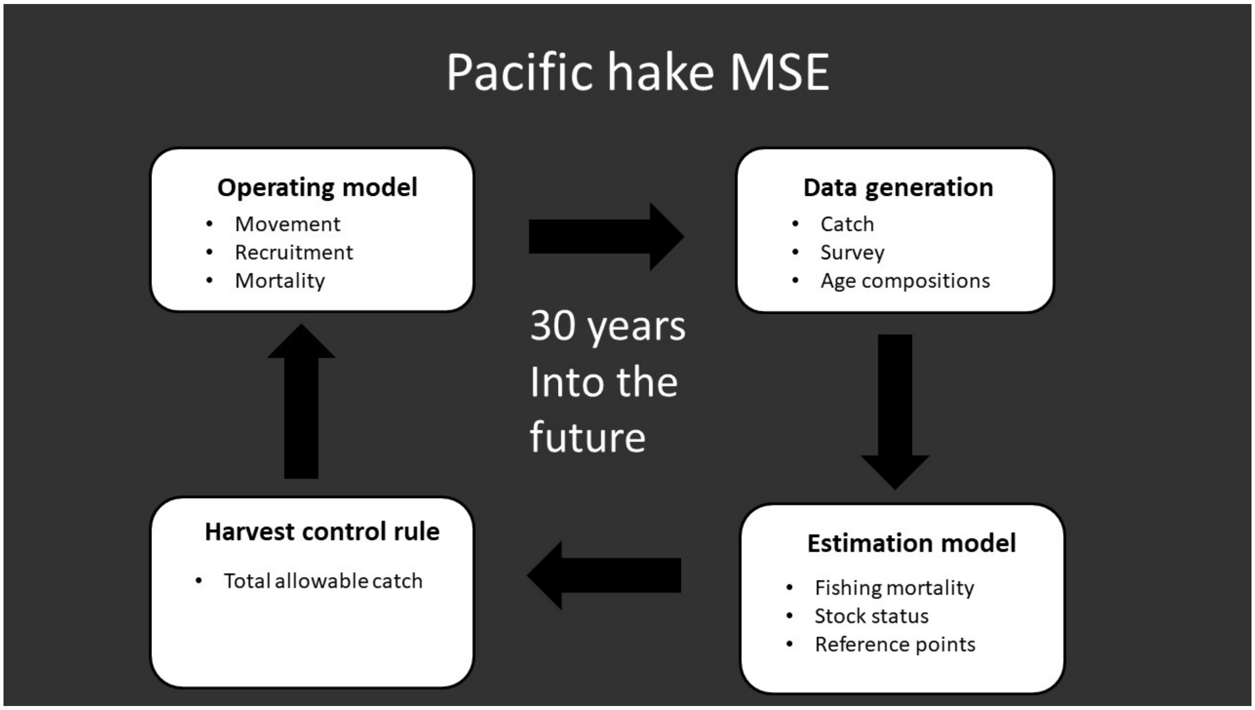

Figure 1: Conceptual description of the four components of the Pacific hake management strategy evaluation (MSE). The operating model has process error on recruitment, and the data generation has measurement error on the survey.

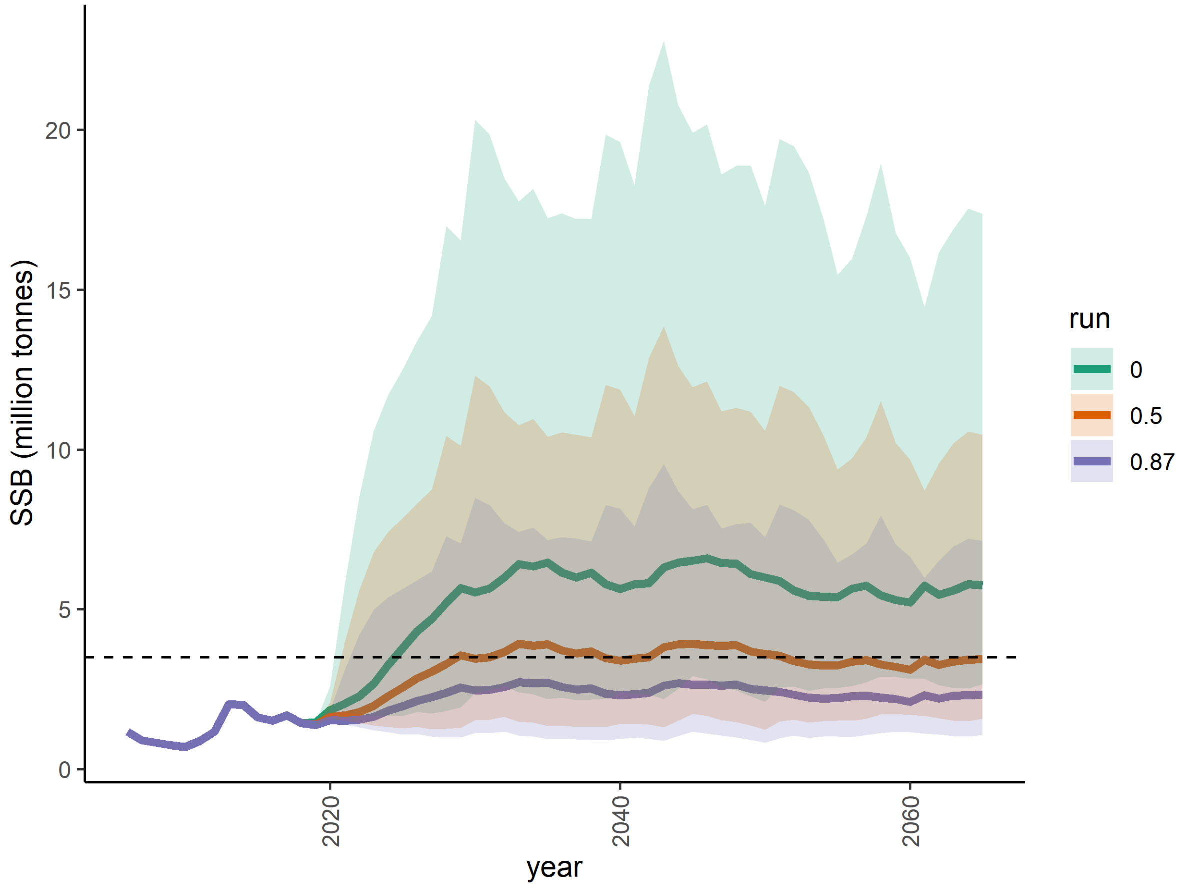

Figure 2: Equilibrium biomass in the future without fishing. The three different colors represent different bias adjustments, and the shaded area is the 5th and 95th percentiles.

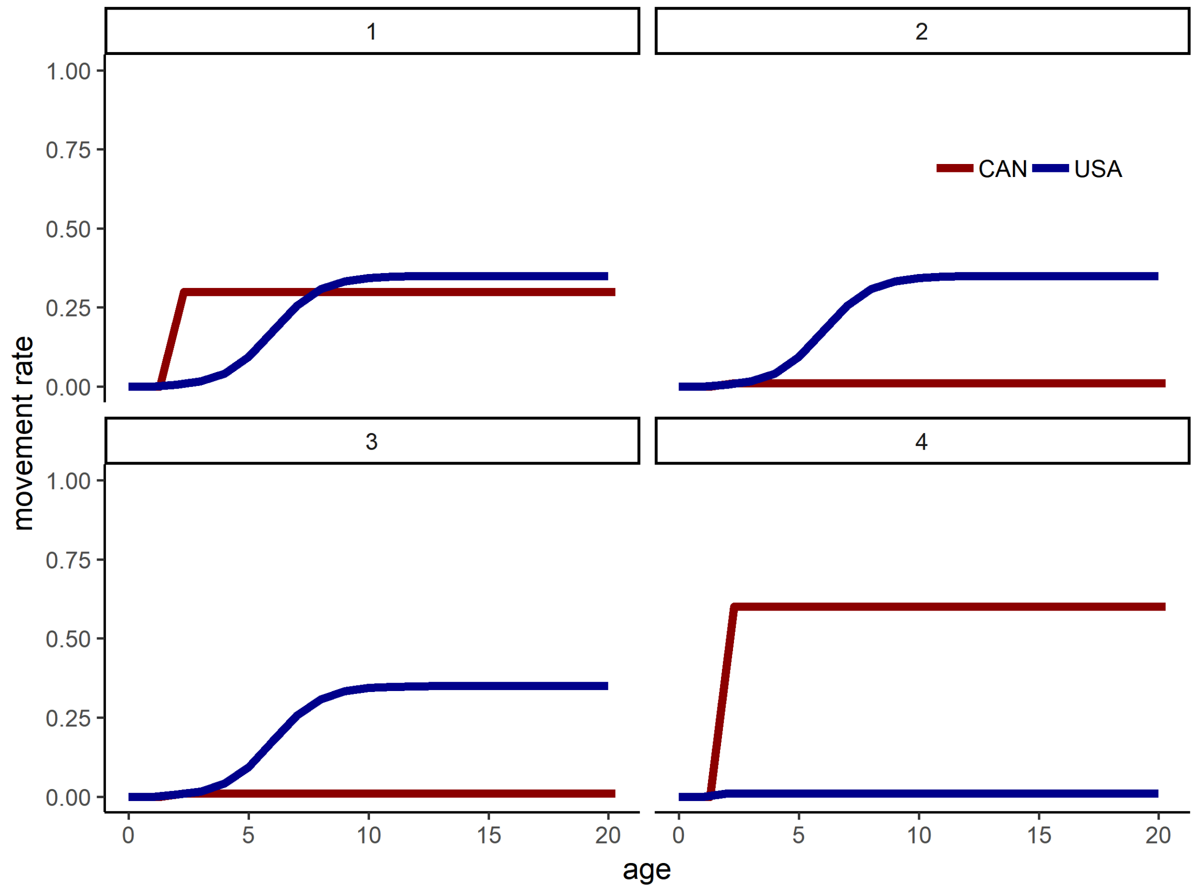

Figure 3: Movement rates as a function of age in the four seasons in the operating model. The number above each plot represents the season (1- Jan-March, 2- April-June, 3-July-Sept, 4-Oct-Dec).

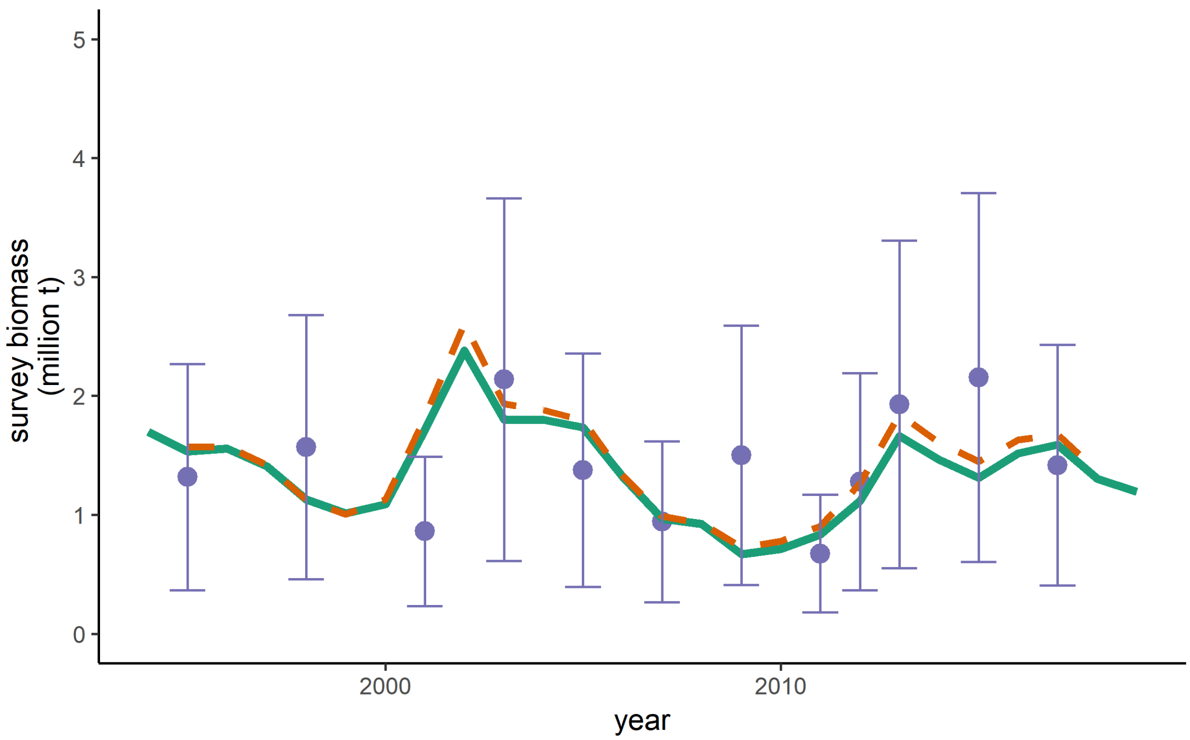

Figure 4: Historical observed survey biomass with its associated uncertainty (purple dots and error bars), and the survey output (without error) from the conditioned operating model (solid green), as well as the survey estimated from the 2018 assessment (dashed orange). The survey is assumed to happen in season 2 of the operating model.

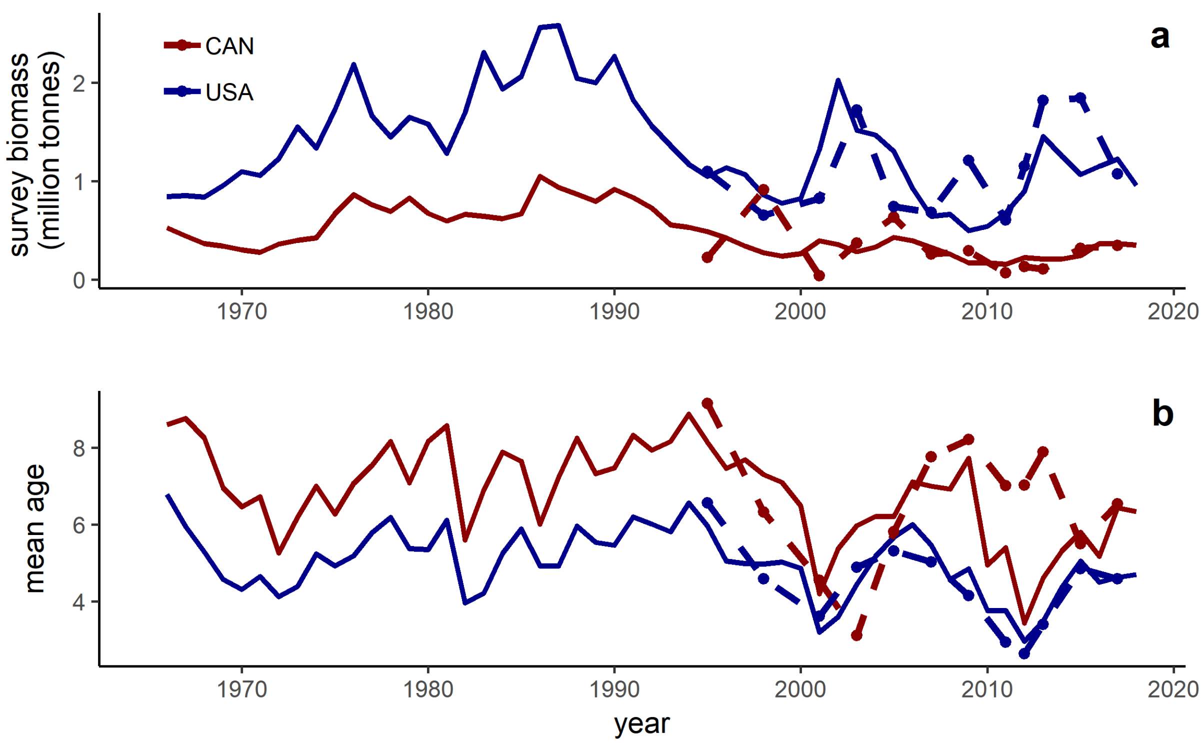

Figure 5: Conditioning of the operating model, with the country specific survey biomass (a) and the average age in the survey (b). Dashed-dotted line represents the data observed in the survey, and the solid lines represents the output from the operating model. Blue represents the fish present in the US and red represents the fish present in Canada.

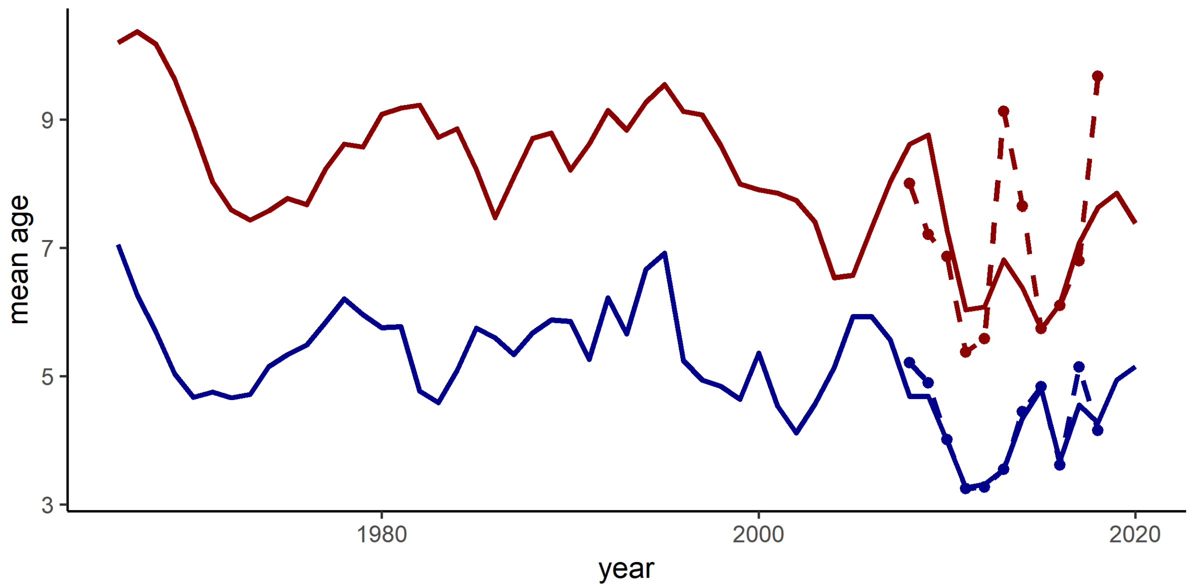

Figure 6: Average age in the catches in the operating model (red is Canada and blue is USA). Solid lines denote the median. The dashed lines with dots denote the observed average ages from the catches.

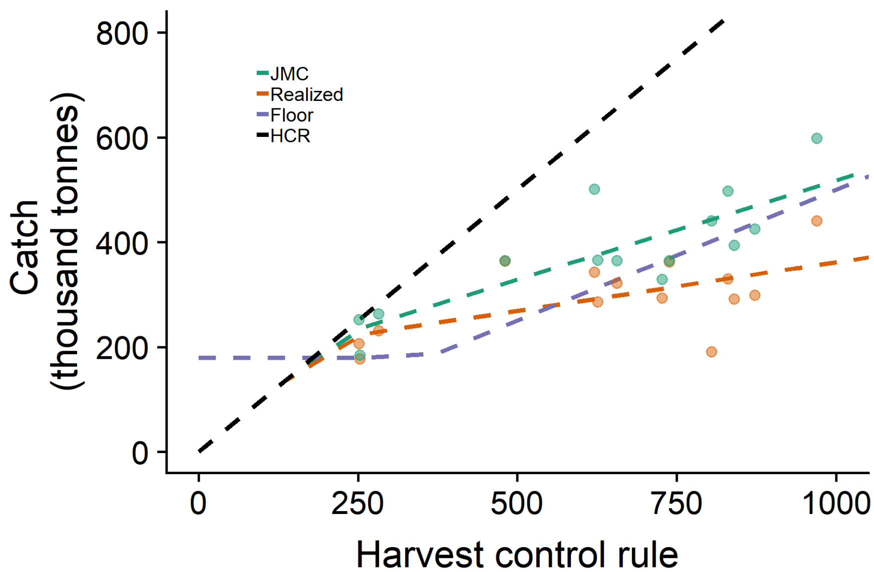

Figure 7: The different catch scenarios, where lines represent the total allowable catch in the four different scenarios (the x-axis being the TAC calculated in equation 18). The dots represent the historical catch given the TAC (JMC mandated quota and the realized catch).

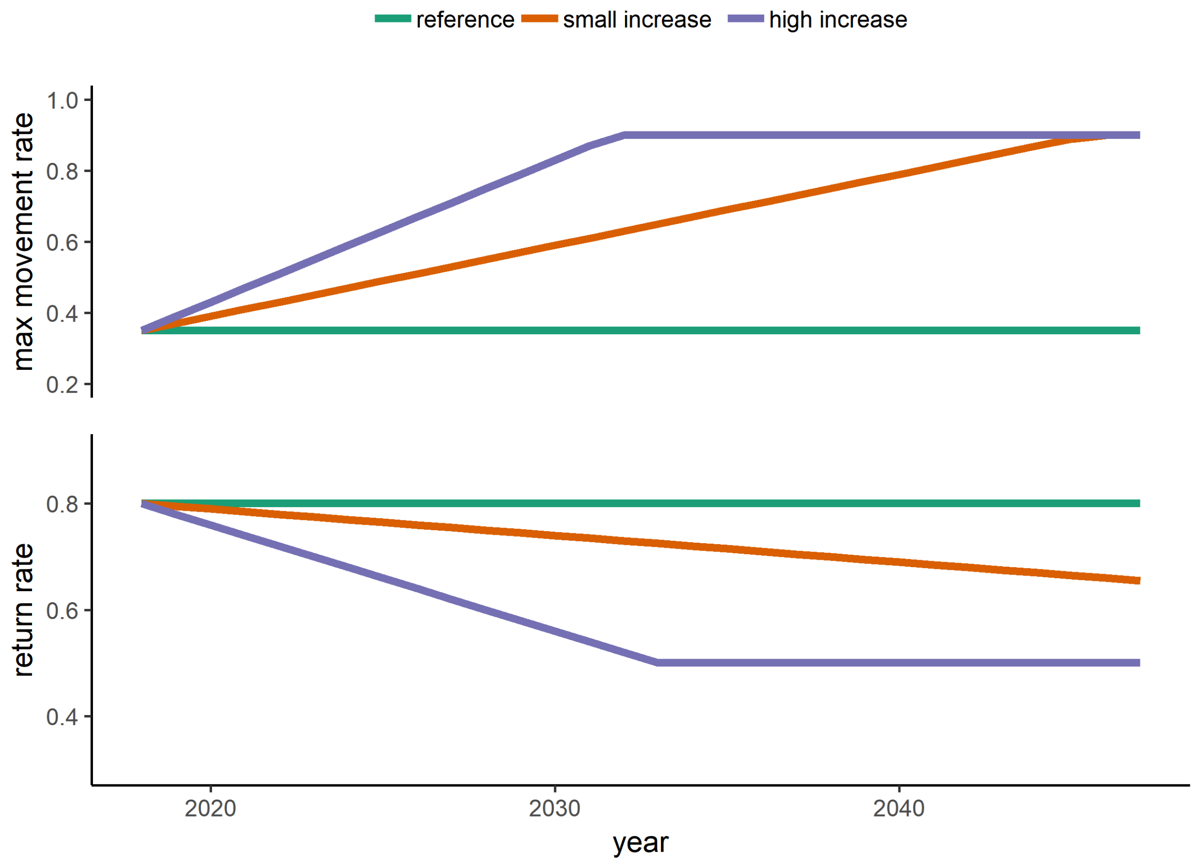

Figure 8: The changes in movement rate in the three different climate scenarios. Max movement rate is κ controlling northward movement in seasons 1 to 3 whereas the return rate is κ_{return} controlling southward movement in season 4 (see also Figure 3).

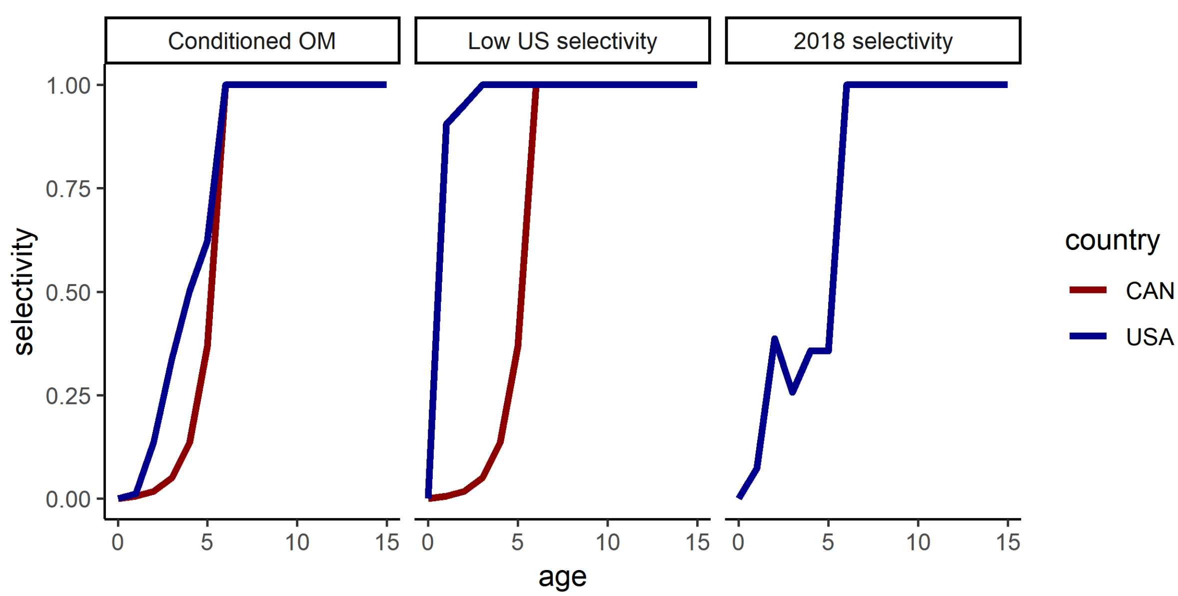

Figure 9: The selectivity in the three different selectivity scenarios. The 2018 selectivity scenario has the same selectivity for both countries.

Appendix A. Glossary of Terms for Pacific Hake Management Strategy Evaluation

40:10 adjustment: a reduction in the overall total allowable catch that is triggered when the female spawning biomass falls below 40% of its unfished equilibrium level. This adjustment reduces the total allowable catch on a straight-line basis from the 40% level such that the total allowable catch would equal zero when the biomass is at 10% of its unfished Equilibrium level. This is one component of the default harvest policy (see below).

Closed-loop simulation model: A subset of an MSE that iteratively simulates a population using an operating model, generates data from that population and passes it to an estimation model, uses the estimation model and a management strategy to provide management advice, which then feeds back into the operating model to simulate an additional fixed set of time before repeating this process.

Conditioning: The process of fitting an Operating Model (OM) of the fish population dynamics to the available data. The aim of conditioning is to select those OMs consistent with the data and reject OMs that do not fit these data satisfactorily and, as such, are implausible.

Default harvest policy (rate): The application of $F_{SPR=40\%}$ (see below) with the 40:10 adjustment (see above). Having considered any advice provided by the JTC, SRG or AP, the JMC may recommend a different harvest rate if the scientific evidence demonstrates that a different rate is necessary to sustain the offshore Pacific Hake/whiting resource.

Estimation Model (EM): a sub-model of a closed-loop MSE simulation model that performs a stock assessment using data from the observation model

Exploitation fraction: A metric of fishing intensity that represents the total annual catch divided by the estimated population biomass over a range of ages assumed to be vulnerable to the fishery (set to ages 2+ in the current hake assessment).

Harvest Control Rule (HCR): A rule that describes how the harvest is to be managed (e.g., catch- or effort-related limits) based on the state of a specified indicator(s) of stock status. Also known as a decision rule. For Pacific hake, see default harvest policy (above).

Harvest Strategy: A pre-agreed framework for recommending or making fisheries management decisions, such as setting catch limits, that is designed to achieve specific management objectives. A fully developed harvest strategy specifies which monitoring data will be collected, how the data will be analyzed, and what harvest control rule(s) will be applied and has been simulation-tested to determine likely performance across a range of uncertainties (e.g., via MSE). Also known as a management procedure.

Management Strategy Evaluation (MSE): An analytical framework that uses closed-loop simulation models to evaluate the performance of alternative harvest strategies against pre-specified objectives, given uncertainty.

Management model: a component of a closed loop simulation model that simulates how the TAC is set in future projections.

Management objectives: Formally adopted goals for a stock and fishery. These include high-level objectives often expressed in legislation, conventions, or similar documents. As the MSE process progresses, they should also include operational biological and socio-economic objectives that are specific and measurable and possibly also associated timelines and minimum required probabilities that can be achieved (see operational objectives below).

Observation Model: A model used to simulate data for use in the MSE (see above). The operating model includes components for the stock and fishery dynamics, as well as the simulation of the data sampling process, potentially including observation error. Cases in the MSE represent alternative configurations of the operating model.

Operating Model (OM): A component of the MSE closed loop simulation model that represents the status and dynamics of the fish population and fishery dynamics, as well as the simulation of the data sampling process, potentially including observation error. There are multiple operating models considered to capture the full range of uncertainties relevant to the MSE exercise.

Operational objectives: A fully specified operational objective has 3 components:

- A **target** or **threshold** value that can be represented in an operating model
- A **time horizon** over which to measure the value
- An acceptable **probability** of achieving the target or avoiding the threshold

Performance metrics: A quantitative expression of a management objective used to compare alternative harvest strategies. Performance metrics values should be compared to the stated objective for the indicator to evaluate how well the candidate harvest strategy achieves the stated management objective.

Reference set (or base-case): A limited set of scenarios, with their associated conditioned OMs, which include the most important uncertainties in the model structure, parameters, and data (i.e. alternative scenarios which have both high plausibility and major impacts on performance of harvest strategies).

Robustness tests: Tests to examine the performance of a harvest strategy across a full range (i.e. beyond the range of the Reference Set of models alone) of plausible scenarios. While plausible, robustness test OMs are typically considered to be less likely than the reference set OMs, and often focus on particularly challenging circumstances with potentially negative consequences to be avoided.

Scenario: A hypothesis concerning resource status and dynamics or fishery operations, represented mathematically as an OM.

Spawning potential ratio (SPR): The ratio of the spawning biomass per recruit under a given level of fishing to the estimated spawning biomass per recruit in the absence of fishing. Often expressed as a percentage, it achieves a value of 100% in the absence of fishing and declines toward zero as fishing intensity increases.

Trade-offs: A balance, or compromise, achieved between desirable but conflicting objectives when evaluating alternative MPs. Trade-offs arise because of the multiple objectives in fisheries management and the fact that some objectives conflict (e.g. maximizing catch vs minimizing risk of unintended depletion).

References

Anon. 2018. Glossary of terms for harvest strategies, management procedures and management strategy evaluation, http://www.tunaorg.org/Documents/MSEGlossary_tRFMO_MSEWG2018.pdf.

Edwards, A.M., I.G. Taylor, C.J. Grandin, and A.M. Berger. 2018. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2018. Prepared by the Joint Technical Committee of the U.S. and Canada Pacific Hake/Whiting Agreement, National Marine Fisheries Service and Fisheries and Oceans Canada. 222 p.

Miller, S.K., Anganuzzi, A., Butterworth, D.S., Davies, C.R., Donovan, G.P., Nickson, A., Rademeyer, R.A. and Restrepo, V., 2018. Improving communication: the key to more effective MSE processes. *Canadian Journal of Fisheries and Aquatic Sciences*, *76*(4), pp.643-656.